COTS for Space - Radiation Characterization of Gyro and IMUs for LEO Operations

Hans Richard Petersen, Reidar Holm, Hans Erik Mathisen, Marius Horntvedt
Sensonor AS
P.O. Box 1004, NO-3194 Horten, Norway; +47 3303 5000
hans.petersen@sensonor.no

ABSTRACT

Since 2012 Sensonor's gyros and IMUs have flown in several CubeSats launched by universities, government R&D and commercial operators worldwide. Today around 200 units are flying and no operator has published or shared much test data that can openly be released to the space community. Together with key customers, the Norwegian Space Agency and the radiation lab of German Fraunhofer Institute an extensive test plan was developed for TID and SEE testing late 2018. The intent was to provide the industry with an open technical document that in detail is sharing all data and failure modes that were observed, and hereby giving valuable and transparent information to communities considering these systems for flight. A total of 42 systems were tested. The systems were characterized before the radiation, then exposed to radiation until failure, then repaired and finally characterized again in order to understand the impact of radiation. The paper covers the test plan, tests that were carried out, detailed failure analysis and a conclusion on the expected capability.

INTRODUCTION

Sensonor has since 2009 produced tactical grade MEMS based IMUs and gyro modules. During this time, more than 25,000 parts, containing more than 75,000 MEMS gyros, have been shipped. Sensonor has earlier been a supplier of high reliable MEMS sensors, including gyros, to demanding safety applications in the automotive industry in high volumes for more than 25 years.

The MEMS gyro in Sensonor's IMUs and gyro modules was originally designed to function in the harsh environment of roll-over detection in cars. Having proven an excellent performance in field for more than 2 million gyros, this was the natural building block for the new generation of IMUs (STIM300) and gyro modules (STIM202 and STIM210) introduced from 2009 and onwards.

The automotive experience has definitely affected the design-, safety- and quality-mindset and has resulted in reliable products that function well in harsh environments. However, the products were not specifically designed for Space applications.

Sensonor's Space heritage started in 2012, when The Aerospace Corporation chose to include the STIM202 in «CubeSats»[1]. The experience was positive. STIM210 is now a preferred gyro in their «CubeSats» and still operational as of late 2018.

Another important Space milestone for Sensonor was February 19, 2017, when the SpaceX Falcon 9 was launched from Kennedy Space Center, Florida, with the Dragon cargo capsule on its way to ISS. The cargo contained STIM products being part of the Raven project to develop autonomous relative navigation[2].

The satellite market is a small market and rumors spread fast. Today there are close to 200 STIM products in use in Space with customers from USA, Russia, Asia and Europe. Sensonor is frequently being contacted by potential customers having certain requirements towards radiation and the need to understand the performance and/or limitations of the STIM products. Therefore Sensonor decided, with financial support from the Norwegian Space Agency, to perform radiation testing to document the performance of STIM300 (IMU) and STIM210 (3-axis gyro module) when exposed to radiation.

TEST OVERVIEW

3 sets of tests have been performed:

Technology Acceptance test is a set of tests to verify that the STIM technology is ready for Space. These tests do not contain irradiation tests, but other types of environmental tests like vibrations, temperatures and EMC.

Single-Event Effect test is a set of tests to characterize the occurrence of single-events in the STIM products when bombarded with protons.

Total Ion Dose test is a set of tests to characterize the effect of irradiation of the STIM products. Half of the parts where powered during the irradiation and half were unpowered.

For all set of tests, the biases (offsets) and scale factors were characterized before and after to investigate the effect each of the different tests could have on the performance. Reference parts, not being exposed to any of the tests, where included in the pre and post characterizations to identify natural variations not caused by the radiation tests themselves.

Characterization of biases and scale factors were not practically feasible to perform between each subtest within one set of tests. Instead, the internal, continuously running self-test of the STIM products, covering a high number of vital parameters, was checked to evaluate whether the specific STIM product under test was fully functional or showed signs of damage.

All parts with a failing self-test after the completion of the set of tests were separated out and subjected to failure analysis and repair to identify the specific failing component(s).

TECHNOLOGY ACCEPTANCE TEST

Definition of test flow

The test flow of the Technology Acceptance test (TA-test) can be found in Figure 1. The test flow is the result of an assessment done by Sensonor after discussing a similar case with the European Space Agency.

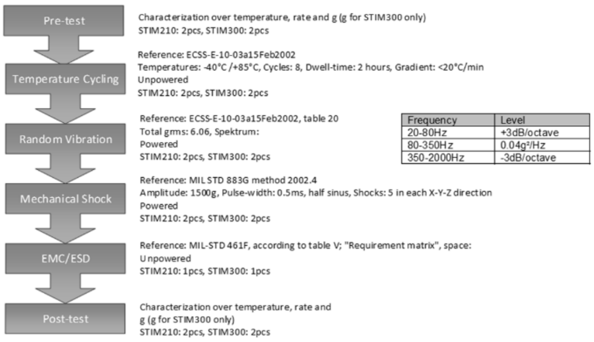


Figure 1: Technology Acceptance test flow

A summary of the EMC/ESD tests according to MIL-STD-461F, table V: "Requirement matrix" for Space is given in Table 1. Some of these tests had already been performed as part of the general qualification program at Sensonor and is denoted as "Generic results" in the table.

Table 1: Summary, EMC/ESD tests

Test type	Standard	Condition	Comment
Conducted emissions	MIL-STD-461F, CE102	10kHz-10MHz	Generic results
Conducted susceptibility, bulk cable injection	MIL-STD-461G, CS114	0.01-200MHz, limit: curve 4 (3)	To be performed
Immunity to bulk current impulse excitation	MIL-STD-461F, CS115	Pulse:30ns, 30pps in 60sec	Generic results
Immunity to damped sinusoidal transients	MIL-STD-461F, CS116	0.01-100MHz	Generic results
Radiated emissions, electric field	MIL-STD-461G, RE102	10kHz-2GHz	To be performed
Radiated susceptibility, electric field	MIL-STD-461F, RS103	2MHZ-18GHz	Generic results
ESD: Immunity to electrostatic discharges	RTCA DO160E, section 25	15kV	Generic results

For all TA-subtests except the EMC/ESD, 2 STIM210s and 2 STIM300s were used. For the EMC/ESD tests, 1 part of from each of the product groups was tested.

Results

The test program has been performed at various facilities as shown in Table 2:

Table 2: List of facilities for TA-test

Test type	Facility
Pre and post tests	Sensonor, Norway
Temperature cycling	Sensonor, Norway
Vibration	Sensonor, Norway
Mechanical shock	Kongsberg Norspace, Norway
EMC	Force Technology, Denmark

The TA-tests are by large the same type of tests used in Sensonor's standard product qualification program. All test steps were passed.

The plots below show the absolute value of the drift between pre- and post-tests. The boxplots represents the interquartile range with the middle line representing the median.

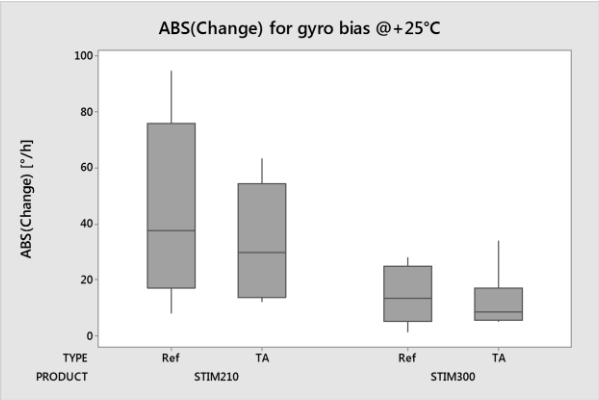


Figure 2: Change in gyro bias

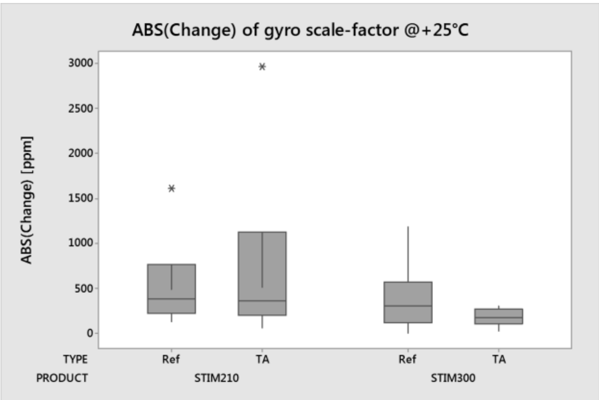


Figure 3: Change in gyro scale factor

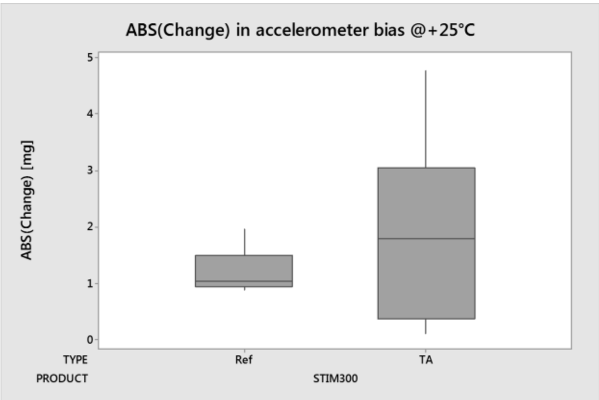


Figure 4: Change in accelerometer bias

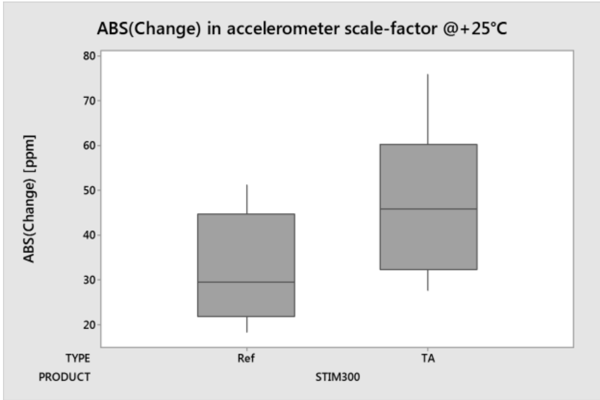


Figure 5: Change in accelerometer scale factor

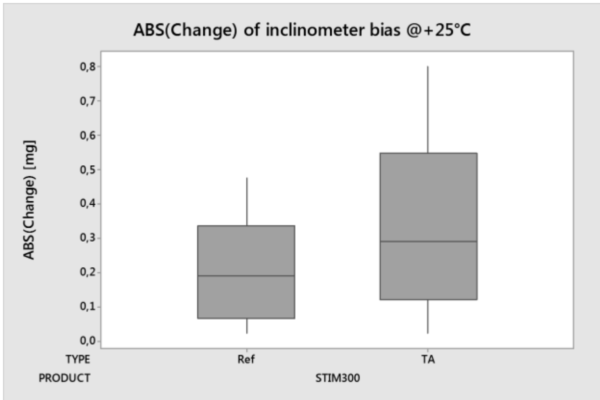


Figure 6: Change in inclinometer bias

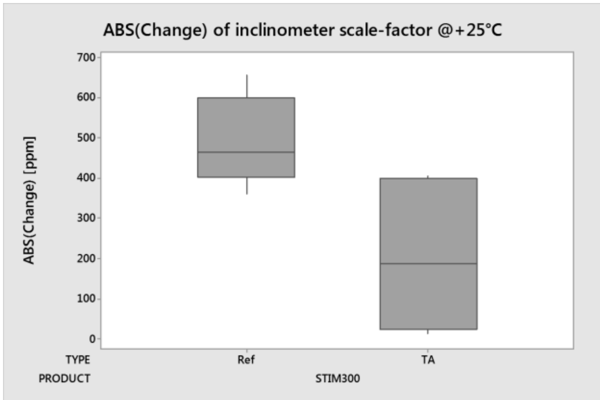


Figure 7: Change in inclinometer scale factor

The changes seen in the parts subjected to the TA-test are comparable to the references or to changes observed in the general qualification programs performed on these products.

The results from the EMC/ESD tests are summarized in Table 3:

Table 3: Summary of results, EMC/ESD tests

Test type	STIM210	STIM300
Conducted emissions	Pass	Pass
Conducted susceptibility, bulk cable injection	Pass	Pass
Immunity to bulk current impulse excitation	Pass	Pass
Immunity to damped sinusoidal transients	Pass	Pass
Radiated emissions, electric field	Pass	Pass
Radiated susceptibility, electric field	Pass	Pass
ESD: Immunity to electrostatic discharges	Pass	Pass

Test summary

The overall assessment of the results obtained in the Technology Acceptance test is summarized in Table 4:

Table 4: Summary of Technology Acceptance test

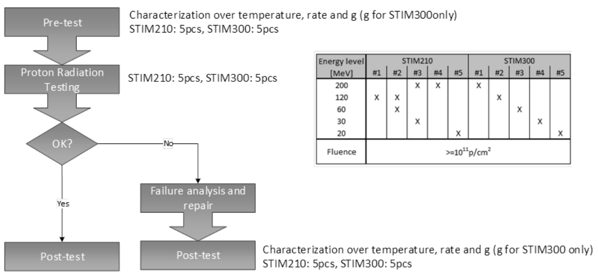
Product	Gyro	Accelerometer	Inclinometer
STIM210	Pass	-	-
STIM300	Pass	Pass	Pass

Results show that both STIM210 and STIM300 have a technology compatible with Space applications.

SINGLE-EVENT EFFECT TEST

Definition of test flow

The test flow of the Single-Event Effect test (SEE-test) can be found in Figure 8:



Energy level [MeV]	STIM210 #1	STIM210 #2	STIM210 #3	STIM210 #4	STIM210 #5	STIM300 #1	STIM300 #2	STIM300 #3	STIM300 #4	STIM300 #5
200			X	X		X				
120	X	X					X			
60		X						X		
30			X						X	
20					X					X
Fluence	>=10^{11}p/cm^2									

Figure 8: Single-Event Effect test flow

The target fluence for each subtest was 1E+11p/cm^2.

5 parts of STIM210 and 5 parts of STIM300 were dedicated to these tests.

The same 2 references from each product group that were used in the Technology Acceptance test are also used here when performance is assessed.

Results

The SEE-test was performed at the Proton Irradiation Facility (PIF) of the Laboratory For Particle Physics, Paul Scherrer Institut, Villigen, Switzerland with the assistance of Dr. Ing. Michael Steffens (Fraunhofer Institute INT in Euskirchen, Germany).

The PIF proton beam is delivered from the COMET (PROSCAN) accelerator and the PIF experimental area is located in the PROSCAN accelerator Hall. The beam delivered to PIF can have primary energies in the range from 230 MeV down to 74 MeV. To avoid a long break of several hours to setup new beam parameters, a beam of 200 MeV initial energy was used for all tests. The beam energy was then degraded locally using the PIF energy degrader to achieve the required energy levels. A moveable XY table with a sample holder and a laser mounted downstream, enabled the positioning of the parts to be tested. The set-up can be seen in Figure 9.

Figure 9: Single-Event Effect test set-up

Single-events were detected by continuously monitoring the supply current and then look for sudden changes in the current. The threshold level for defining a single-event was set to 10mA between each current measurement. At some instances latch-up occurred with a large current (>1A) flowing. In these cases the part needed to be restarted to resume normal operation by cycling power.

The achieved fluence is shown in Table 5:

Table 5: Achieved fluence

Energy [MeV]	Product	Fluence [10^{11}p/cm^2]				
		#1	#2	#3	#4	#5
200	STIM210	0.28				
120	STIM210		1.00			
60	STIM210			0.99		
32	STIM210				1.00	
20	STIM210					0.68
200	STIM300			0.16	0.29	
120	STIM300	1.00	0.21			
60	STIM300		0.95			
32	STIM300			1.00		
20	STIM300					1.01

The time at which each single-event occurred was recorded and the fluence at each single-event was calculated. The cross section could then be calculated by taking the number of events and divide by the fluence giving a measure for the likeliness of a single-event to occur. Results are plotted in Figure 10 and Figure 11 as function of energy level with error bars calculated for a confidence level of 0.95:

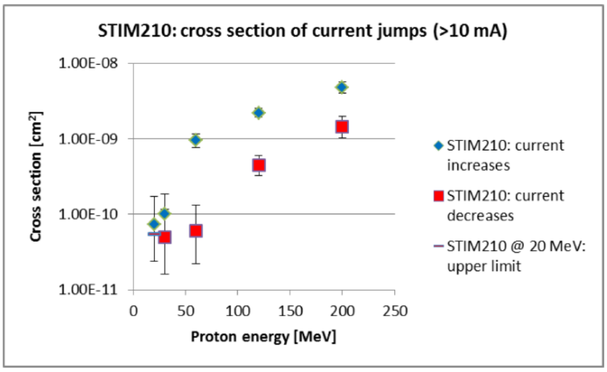


Figure 10: STIM210 cross section of single-events

At 20 MeV no events of current decrease were observed, so only the statistical upper limit of the cross section is given.

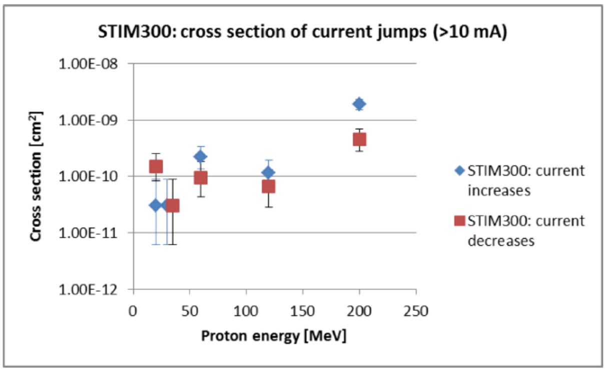


Figure 11: STIM300 cross section of single-events

In comparison the cross sections at high energies are lower for the STIM300 than for the STIM210 and at approximately the same level for lower energies. At or below 60 MeV additional effects due to TID may contribute. However for the STIM210, the rather strong correlation of the cross section with the proton energy down to the lowest energies of the tests indicates that the current jumps are mostly given by single-event effects. For the STIM300 at low energies this is not indicative from the evaluation.

In Table 6 the results of the self-test check after the SEE-test are summarized. The check had three outcomes: pass, fail or no communication.

Table 6: Summary of self-test status for STIM210

Energy	STIM210					STIM300				
[MeV]	#1	#2	#3	#4	#5	#1	#2	#3	#4	#5
200										
120										
60										
32										
20										

Not tested at energy
Passed at post-irradiation test
Failed at post-irradiation test
No communication at post-irradiation test

The parts passing the self-test were characterized at Sensonor.

The plots below show the absolute value of the change between pre- and post-tests of the functional parts after the SEE-test:

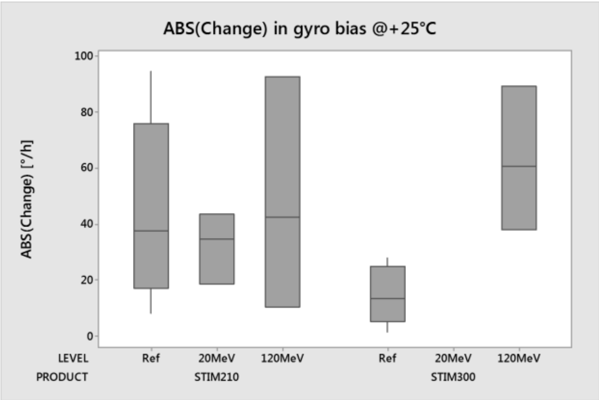


Figure 12: Change in gyro bias

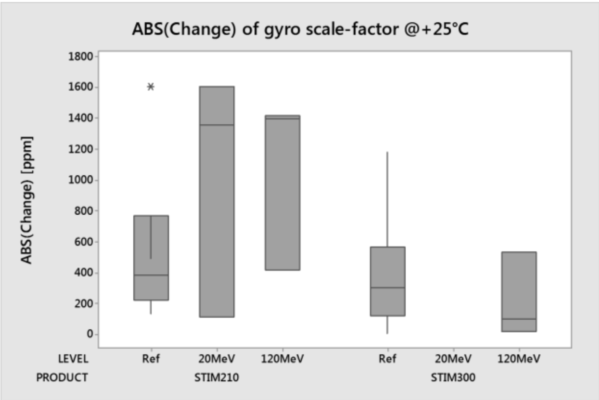


Figure 13: Change in gyro scale factor

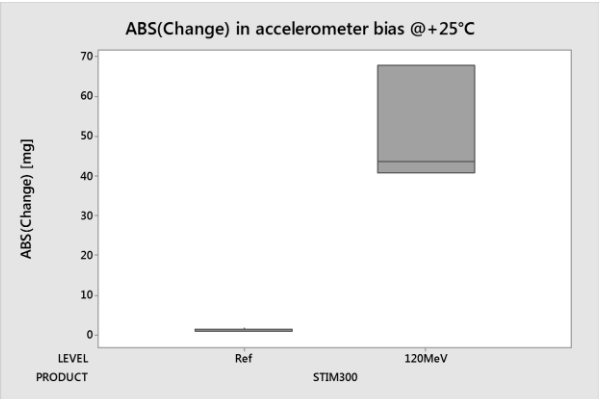


Figure 14: Change in accelerometer bias

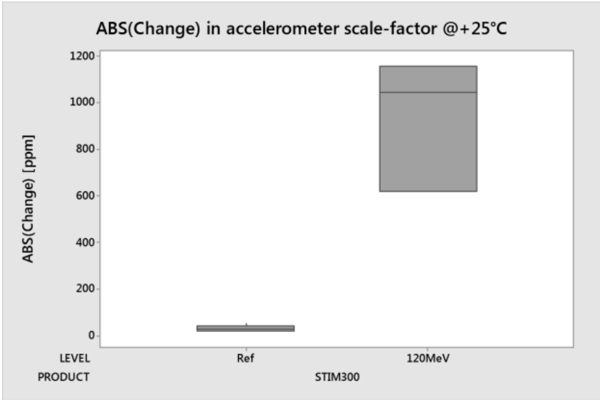


Figure 15: Change in accelerometer scale factor

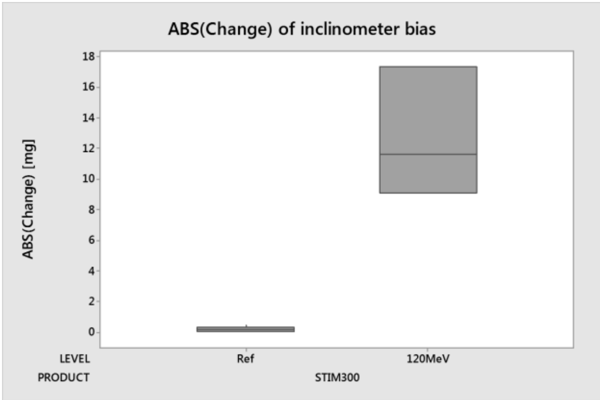


Figure 16: Change in inclinometer bias

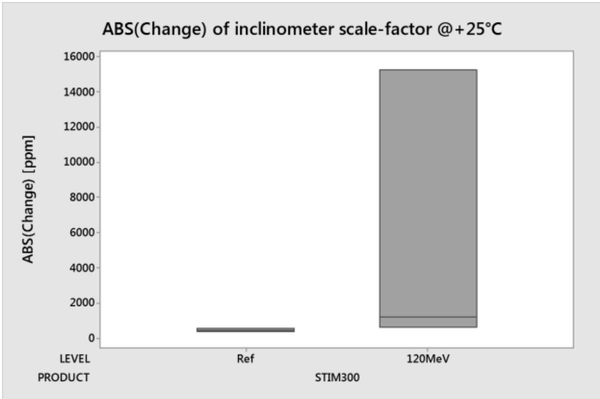


Figure 17: Change in inclinometer scale factor

The changes observed in the gyros of the parts still functional after SEE-tests are similar to the references or to the changes observed in the general qualification programs performed on these products.

The changes observed in the accelerometers and inclinometers (STIM300 only) are substantial compared to changes seen in references and general qualification programs.

Test summary

The cross section has been experimentally derived for STIM210 and STIM300. Cross section for STIM210 correlates well with proton energy level, suggesting that the cross section reflects single-events only. For STIM300 the cross section is somewhat lower at higher proton energy levels and the correlation to proton energy level is not as evident.

The results of the pre- and post-tests for the parts functioning after the SEE-test are summarized in Table 7:

Table 7: Summary of changes seen in performance after Single-Event Effect test

Product	Gyro	Accelerometer	Inclinometer
STIM210	Pass	-	-
STIM300	Pass	Bias+SF affected	Bias+SF affected

TOTAL ION DOSE TEST

Definition of test flow

The test flow for Total Ion Dose test (TID-test) can be found in Figure 18:

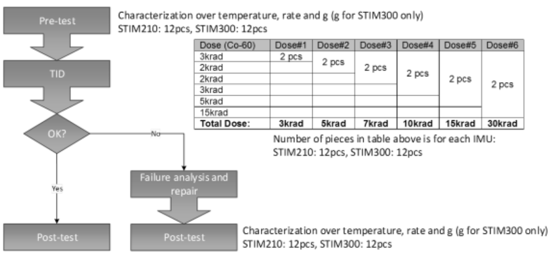


Figure 18: Total Ion Dose test flow

12 parts of STIM210 and 12 parts of STIM300 were dedicated to these tests. For each dose one of the two parts from each product group will be powered during the irradiation, the other unpowered.

The same 2 references from each product group that were used in the Technology Acceptance test are also used here when performance is assessed.

Results

The TID-test was performed at the Nuclear Effects in Electronics and Optics (NEO) laboratory at Fraunhofer Institute for Technological Trend Analysis in Euskirchen, Germany. Their Co-60 source TK1000B gave a dose rate of 1400 rad/h.

A custom built sample holder was manufactured to fix the samples under the radiation source, dissipate heat from the parts under test and ensure that the samples were homogeneously irradiated. To fit the point symmetry of the Co-60 source, the parts were arranged in a circular pattern. A PMMA top plate was added to serve as a charge equalization layer. The actual set-up can be seen in Figure 19.

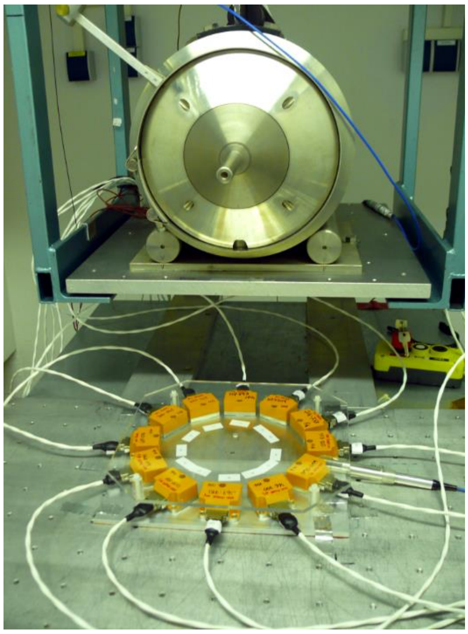


Figure 19: Total Ion Dose test setup

After each irradiation step, the self-test of all parts was checked to evaluate whether the parts were still fully functional or showed signs of damage. The result of this is summarized in Table 8 and Table 9.

Table 8: Summary of self-test status for STIM210

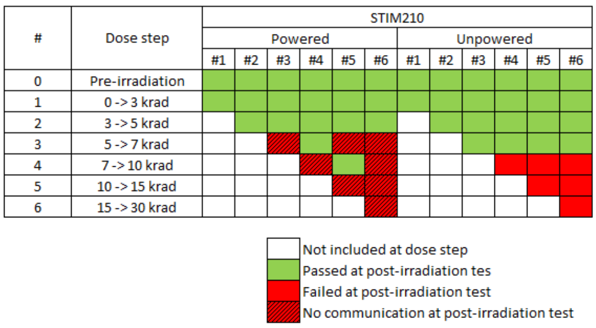


Table 9: Summary of self-test status for STIM300

#	Dose step	STIM300											
		Powered						Unpowered					
		#1	#2	#3	#4	#5	#6	#1	#2	#3	#4	#5	#6
0	Pre-irradiation												
1	0 -> 3 krad												
2	3 -> 5 krad												
3	5 -> 7 krad												
4	7 -> 10 krad												
5	10 -> 15 krad												
6	15 -> 30 krad												

Not included at dose step
Passed at post-irradiation tes
Failed at post-irradiation test
No communication at post-irradiation test

The results shown in Table 8 and Table 9 are quite similar for the two products. Based on the self-test, parts are functional up to a total ion dose of 5krad when powered and 7krad when unpowered. Further, for powered parts above 5krad the communication fails when attempting to check the self-test, whilst unpowered parts above 7krad have a self-test indicating signs of damage. This points towards different failure mechanisms for powered and unpowered devices. One part (STIM210#5 powered) started to communicate again after 10krad of exposure even if it failed communicating after 7krad.

The parts passing the self-test were characterized at Sensonor. The following figures show the absolute value of the change between the characterization done before and after the TID-test. The plots in the figures differentiate between powered and unpowered parts. In all plots the same data for the reference parts will appear twice to serve as reference for both the powered and unpowered results.

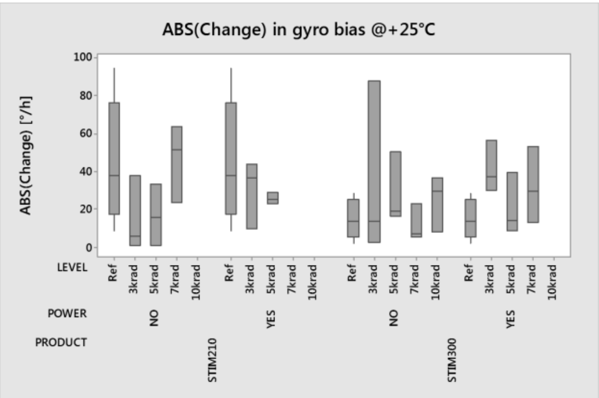


Figure 20: Change in gyro bias

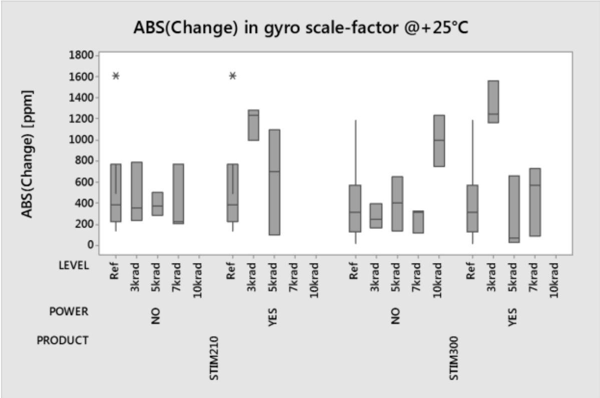


Figure 21: Change in gyro scale factor

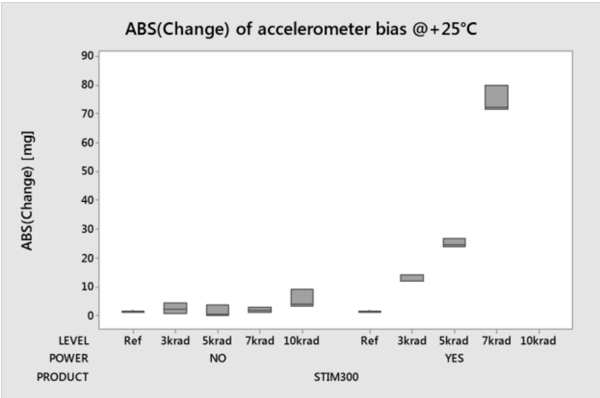


Figure 22: Change in accelerometer bias

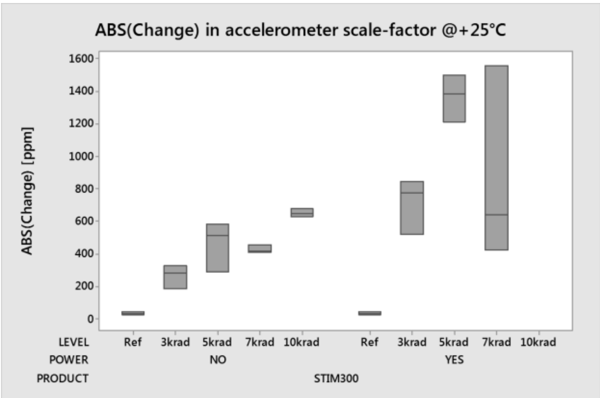


Figure 23: Change in accelerometer scale factor

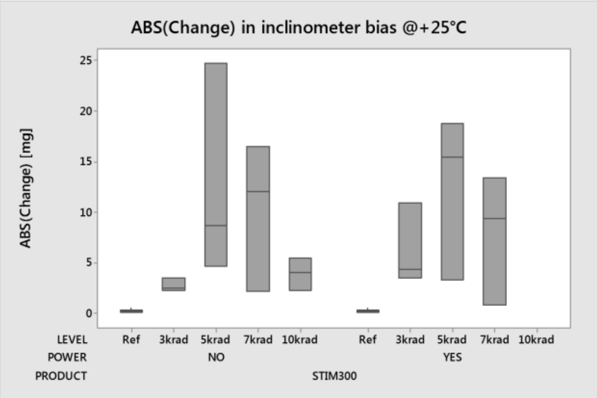


Figure 24: Change in inclinometer bias

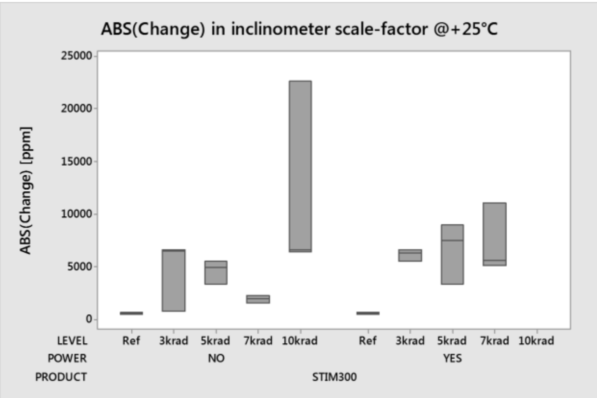


Figure 25: Change in inclinometer scale factor

The changes observed in the gyros of the parts still functional after TID-test are similar to the references or to changes observed in the general qualification programs performed on these products. This is correct even at TID-levels of 10krad, the largest level any of the parts survived in this test.

On the other hand, the shifts observed in the accelerometers and inclinometers (STIM300 only) are substantial compared to changes seen in references or the general qualification programs. There is a clear relationship between the size of the shift and the dose level. In addition the powered parts show a higher shift than the unpowered, except for inclinometer bias.

Test summary

All parts passed the self-test check after irradiation dose levels of 3krad and 5krad. All unpowered parts even passed the self-test check at 7krad.

Characterization of gyro performance shows acceptable performance on all surviving parts (up to 10krad).

Characterization of accelerometer and inclinometer performance shows significant changes in bias and scale factor.

The overall assessment of the results obtained in the Total Ion Dose test is summarized in Table 10:

Table 10: Summary of Total Ion Dose test

Product	Gyro	Accelerometer	Inclinometer
STIM210 - powered - unpowered	 Pass ≤ 5krad Pass ≤ 7krad	 - -	 - -
STIM300 - powered - unpowered	 Pass ≤ 5krad Pass ≤ 7krad	 Bias+SF affected Bias+SF affected	 Bias+SF affected Bias+SF affected

FAILURE ANALYSIS

All parts failing the self-test check after SEE-test and TID-test were subjected to failure analysis. The parts were carefully opened and analyzed to assess which component(s) in the system that had failed. Identified components were replaced until the self-test gave a pass result.

Failures from SEE-test

All the parts subjected to the SEE-test were put in quarantine for just over 2 months until the radiation level had reached a safe level for their return to Sensonor.

As a first step in the failure analysis, the self-test check was repeated. The results are summarized in Table 11.

Table 11: Comparing failure status

Product	Device#	Energy level	Status after SEE-test	Status at start of failure analysis
STIM210	1	200	Self-test failed	Self-test OK
STIM210	3	60	No comm	No comm
STIM210	4	32	No comm	No comm
STIM300	1	120	No comm	Self-test OK
STIM300	2	60	No comm	Self-test failed
STIM300	3	200	Self-test failed	Self-test failed
STIM300	4	200	Self-test failed	Self-test failed
STIM300	5	20	Self-test failed	Self-test failed

Two parts (one STIM210 and one STIM300) had recovered after 2 months rest after the proton exposure. In Figure 26 is a Pareto diagram of the failing components in the parts from the SEE-test:

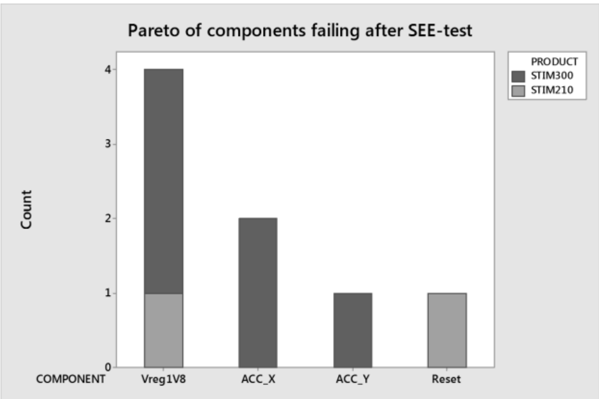


Figure 26: Pareto of failing components, SEE-test

The 1.8V regulator is clearly the weakest part when it comes to proton irradiation. Other components failing are the accelerometers (STIM300) and the reset circuit (STIM210).

Failures from TID-test

In Figure 27 is a Pareto diagram of the failing components in the parts from the TID-test:

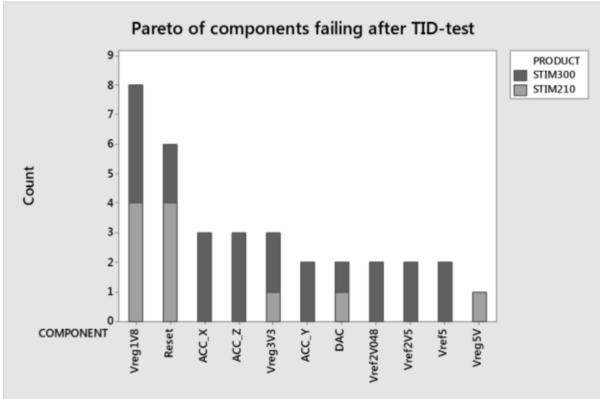


Figure 27: Pareto of failing components, TID-test

The Pareto diagram shows a clear overrepresentation of the 1.8V regulator and the reset circuit.

The TID-test revealed a difference in failure behavior, ref. Table 8 and Table 9, where the powered parts typically resulted in a failing communication and the unpowered parts resulted in a failure in the self-test. Figure 28 shows the Pareto based on Figure 27 where the counting of the failing components has been split into whether the part was powered or unpowered.

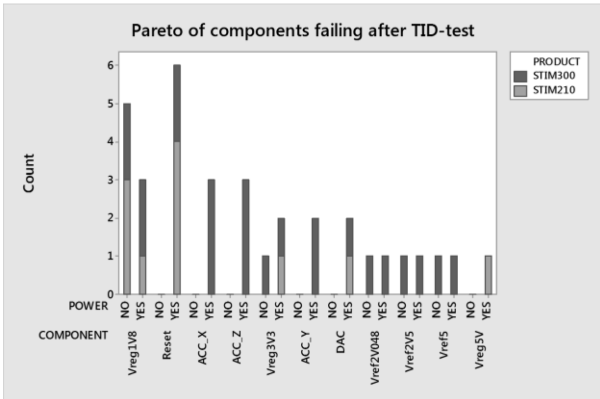


Figure 28: Pareto of failing components, TID-test

The plot reveals that the reset circuit only fails in the case of powered parts. This is also true for the accelerometers and DAC.

The number of components failing at the different irradiation dose levels has also been investigated. Figure 29 shows the number of failing components as function of total dose.

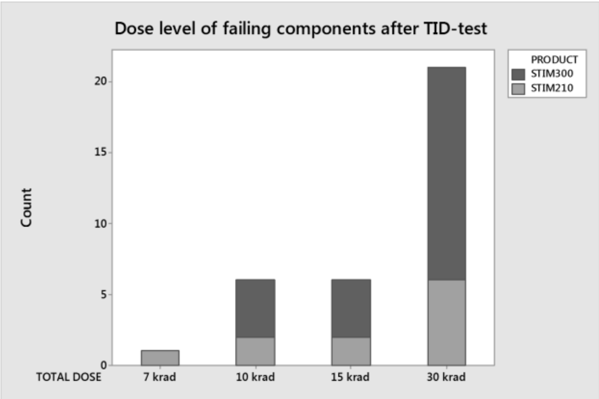


Figure 29: Dose level of failing components, TID-test

The results clearly show an increase in number of components with increasing dose level. This seems to be rational.

In Figure 30 and Figure 31 the type of components failing at the different dose levels are plotted for STIM210 and STIM300 respectively.

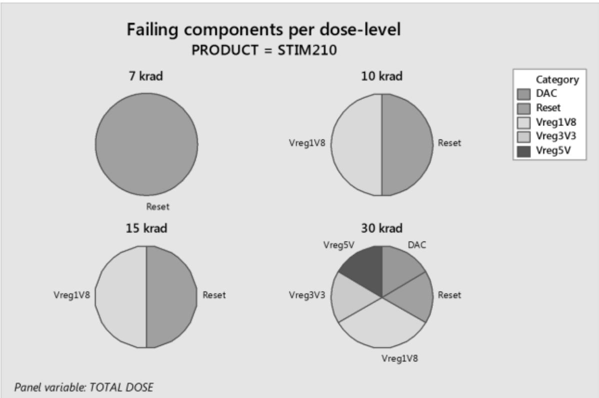


Figure 30: STIM210: Dose level of failing components

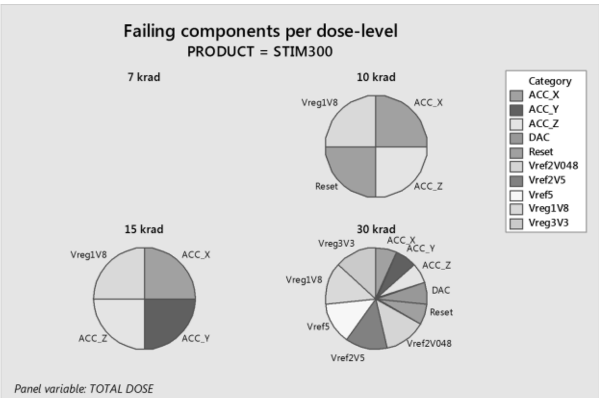


Figure 31: STIM300: Dose level of failing components

At 7krad, the only component failing is the reset circuit (STIM210). At 10 and 15krad, the 1.8V regulator is also failing together with the accelerometers (STIM300 only). When reaching 30krad several other components like regulators and references start to fail.

More details of the failing components can be found in Table 12.

Table 12: Summary of failing components

Component	Manufacturer part number	Manufacturer
Reset	TPS3808G01DBVTG4	Texas Instruments
Vreg1V8	LT1763CDE-1.8#PBF	Linear Technology
ACC (X,Y,Z)	MS9010.A	Colibrys
DAC	AD5308ARUZ	Analog Devices
Vreg3V3	TPS62290DRVTG4	Texas Instruments
VReg5V	LT1763CDE-5#PBF	Linear Technology
VRef2V048	ADR440ARMZ	Analog Devices
VRef2V5	ADR441ARMZ	Analog Devices
VRef5V	ADR445ARMZ	Analog Devices

ASSESSMENT OF RESULTS

Fraunhofer Institute INT in Euskirchen, Germany, has made a very general assessment to try to relate the obtained results towards the radiation levels found in low Earth orbits (LEOs).

A 10 year mission in heliosynchronous orbit at 800 km altitude was used as case for the simulations. The tool used for generation of the orbit and estimation of the radiation environment and levels was the Space Environment Information System (SPENVIS) and the tools and models contained therein.

To estimate the total ionizing dose behind aluminum shielding, e.g. the outer hull of the satellite, the SHIELDOSE2Q simulations were used. This is a standard tool for this type of estimations. However it has some intrinsic limitations and may not be fully applicable to the STIM210 or STIM300. This is mainly because the total dose is simulated in silicon positioned directly behind the aluminum shield, whereas in the tests reported here the parts are more complex and feature a thick aluminum package themselves.

With a 14 mm of aluminum shield the total dose over 10 years drops below 5 krad(Si) in these simulations, and thus to the TID level where all parts were still functional.

Further, the MFLUX tool in SPENVIS was used to calculate the shielded flux of protons. Due to limitations in the tool, a thickness of 11.1 mm aluminum (the next lower value to 14 mm) was chosen for these simulations. In this case, the highest contribution in the energy spectrum comes from protons of approx. 50-100 MeV energy with fluxes in the order of 100 p/cm2/s which accumulate to 3.2E10 p/cm2 over the 10 year mission. Comparing this to the experimental cross section of the current jumps from the SEE-test, several 10s of events can be expected in this case, even behind 11 mm of aluminum.

The results obtained in the SEE-test and TID-test coincide well with results independently reported from several customers.

CONCLUSIONS

Both STIM210 and STIM300 passed the Technology Acceptance test verifying that the products have a general robustness to function in Space.

Both products survive TID radiation levels up to 5krad when powered and up to 7krad when unpowered. This radiation level is considered within reach for applications in low Earth orbit. The high performance of the gyros is maintained at radiation levels up to 5krad. However, the performance of the accelerometers and inclinometers in STIM300 is degraded when exposed to radiation and their use in Space should be carefully evaluated.

The cross section related to single-events has been established for STIM210 and STIM300. In the simulated case of a 10 year mission in heliosynchronous orbit at 800 km with 11.1mm aluminum shielding, several 10s of events must be expected. For the parts surviving the Single-Event Effect test, the gyro performance is maintained, while the accelerometers and inclinometers are degraded after proton irradiation.

Failure analysis of the failing parts revealed the 1.8V regulator, the reset circuit and the accelerometers (STIM300 only) to be the least robust components with respect to radiation.

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